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FINAL REPORT

NASA Planetary Materials and Geochemistry Grant NAG 5-4215

Pristine Igneous Rocks and the Genesis of Early Planetary Crusts

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Our studies are highly interdisciplinary, but are focused on the processes and products of early planetary and asteroidal differentiation, especially the genesis of the ancient lunar crust. The compositional diversity that we explore is the residue of process diversity, which has strong relevance for comparative planetology.

Most of the accessible lunar crust consists of materials hybridized by impact-mixing. Our lunar research concentrates on the rare pristine (unmixed) samples that reflect the original genetic diversity of the early crust. Among HED basalts (eucrites and clasts in howardites), we distinguish as pristine the small minority that escaped the pervasive thermal metamorphism of the parent asteroid's crust. We have found a correlation between metamorphically pristine HED basalts and the similarly small minority of compositionally evolved "Stannern trend" samples, which are enriched in incompatible elements and titanium compared to main group eucrites, and yet have relatively high *mg* ratios. Other topics under investigation included: lunar and SNC (martian?) meteorites; igneous meteorites in general; impact breccias, especially metal-rich Apollo samples and polymict eucrites; siderophile compositions of the lunar and martian mantles; and planetary bulk compositions and origins.

Our studies of lunar meteorites included the unique pairing of Yamato-793274 with Queen Alexandra Land 94201. These two probably are not paired in the conventional (Earth-atmosphere-entry) sense, but are paired in the sense of derivation from the same source crater (launch event) on the Moon. We based this inference on general similarity of the rocks, which are both mixed mare-highland regolith breccias, but in particular on a striking similarity in the clustered compositions of mare pyroclastic glasses within the breccias.

We found that among martian meteorites, siderophile element concentrations show good correlations with compatible-lithophile elements MgO and Cr, as is also observed for mafic-igneous Earth rocks and (albeit less unequivocally) for lunar basalts. These correlations imply that the martian mantle, like the terrestrial mantle, contains highly siderophile elements at roughly 0.5% of the chondritic concentrations. In the case of Earth, the siderophile data have

been variously interpreted as reflecting metal/silicate differentiation at the extremely high pressure of the deep terrestrial mantle, or as the result of a late veneering of the planet by roughly 0.5% of undifferentiated matter ("late" in the sense that it arrived after cooling and/or oxidation had isolated the core from the mantle). In the case of Mars, there is no such ambiguity, because pressure at the martian core/mantle boundary is much less than in the case of the Earth, so high pressure modification of the metal-silicate partitioning cannot be a factor.

We made a further contribution to the debate about origin of the putatively fossiliferous carbonates in the ALH84001 martian meteorite. Based on comparison between major element zoning and the great oxygen isotopic heterogeneity within the carbonates, it was shown that the carbonates could not possibly have formed in a closed system at high temperature, which effectively rules out the shock-melt origin proposed by Ed Scott and his coworkers.

We reported the discovery of Los Angeles, the most differentiated martian meteoritic basalt. This meteorite is unique for its low *mg* ratio, extremely low chromium, and high concentrations of incompatible trace elements. The low *mg* ratio resulted in the formation of a remarkably high proportion of pyroxferroite, now decomposed into symplectites of augite+fayalite+silica. In a follow-up paper (recently submitted), we describe these symplectites in greater detail, and note that they are especially abundant in the smaller of the two Los Angeles stones. We show that despite their dissimilar modes, the two stones clearly originated in a single igneous body. We note a uniquely steep correlation between Cr and *mg* in the pyroxenes, which implies that during crystallization the pyroxene/melt partition coefficient was extraordinarily high. This in turn suggests that oxygen fugacity was near the high end of the range previously proposed for Los Angeles (and for shergottites in general)..

We measured porosity for eight lunar meteorite breccias and calculated porosity for two more on the basis of literature density measurements. Lunar meteorite regolith breccias display systematically low porosity in comparison to otherwise analogous Apollo regolith breccias. Among seven meteoritic regolith breccias, porosity ranges from 1 to 11%, and averages 7.5%, whereas for 44 analogous Apollo samples (porosities mostly calculated from literature density data) the average is 25 %. This disparity probably reflects mainly a bias in favor of strong, compact breccias among fragments that manage to survive the violent process of launch to lunar escape velocity (2.38 km/sec). In addition, compaction during launch may play an important role. The population of lunar meteorites is clearly not a random, unmodified sample of lithic materials near the surface of the parent body.

Very recently (only partly within the time frame of this grant), we obtained data for the first three lunar meteorite impact melt breccias. Compared to their Apollo and Luna counterparts, these samples are relatively poor in both incompatible and siderophile trace elements. The incompatible elements are apparently concentrated in a small region of the Moon's central nearside, which happens to coincide closely with the small Apollo/Luna sampling region. The (random) source craters of lunar meteorites are mostly far enough from that central nearside region to be dramatically less enriched in incompatible elements. The siderophile trends are more enigmatic, but the simplest explanation is that the central nearside megaregolith was enriched in these elements by a very small number (1-2?) of extraordinary impact events. Data for lunar meteorites were also used to show that the present calibration of the Lunar Prospector global thorium map needs major (downward) revision. The need for the revision can be shown by various approaches, including discrepancy vs. an earlier Apollo global Th data set. The revisions imply the Moon is modestly endowed, and quite similar to Earth's mantle, in terms Th and other refractory lithophile elements. Finally, we noted an anticorrelation between Al_2O_3 and *mg* among KREEP-free lunar regolith materials (including many lunar meteorites). Extrapolation of this trend, even making a range of assumptions, clearly implies a relatively high *mg* ratio for the Moon, again manifesting strong similarity to Earth's mantle.

Papers generated from NAG 5-4215 (12/15/98-12/14/01):

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- WARREN P. H. (1999) Reply to the Comment of Scott et al. on "Petrologic evidence for low temperature, possibly flood evaporitic origin of carbonates in the ALH84001 meteorite." *Jour. Geophys. Res.-Planets* **104**, 24217-24221.
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- RUBIN A. E., WARREN P. H., GREENWOOD J. P., VERSHIH R. S., LESHIN L. A., HERVIG R. L., CLAYTON R. N. and MAYEDA T. K. (2000) Los Angeles: The most differentiated basaltic martian meteorite. *Geology* **28**, 1011-1014.
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- WARREN P. H. (2002) "New" lunar meteorites: II. Implications for composition of the global lunar surface, of the lunar crust, and of the bulk Moon. *Meteor. Planet. Sci.*, submitted.
- WARREN P. H., GREENWOOD J. P. and RUBIN A. E. (2002) Los Angeles: A tale of two stones. *Meteor. Planet. Sci.*, submitted.



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June 13, 2002

National Aeronautics and Space Administration
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ATTN: David Lindstrom, 077.0
Technical Officer

SUBJECT: Final Technical Report for NAG5-4215
P.I. Professor Paul H. Warren

Dear Dr. Lindstrom:

In accordance with the requirements of the subject grant, please find enclosed the original of the final technical report. No patents or inventions were first reduced under the support of this award.

Sincerely yours,

A handwritten signature in black ink, appearing to read "Paul H. Warren".

Paul H. Warren
Principal Investigator

A handwritten signature in black ink, appearing to read "Keith R. Olwin".

Keith R. Olwin
Departmental Research Associate

ENCLOSURE

cc: Tracey A. Jones, NASA Grant Specialist
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